1-1-2012

Future fire regimes of Australian ecosystems: new perspectives on enduring questions of management

Ross A. Bradstock
University of Wollongong, rossb@uow.edu.au

Richard J. Williams
CSIRO Tropical Ecosystems Research Centre

A Malcolm Gill
Australian National University

Future fire regimes of Australian ecosystems: new perspectives on enduring questions of management

Abstract

This book provides a contemporary overview of the state of knowledge of fire as a shaper of biodiversity and ecosystems in Australia, along with insights into the way in which a 'flammable Australia' may fare under future climate change. It comes at the end of a decade (2000 to 2010) of extraordinary fire activity in Australia, matched by heightened public interest in fire and debate about its management. The decade commenced with major fire activity between 2000 and 2002 in the central and north western deserts (Nano et al. 2012, Chapter 9), at scales not seen in decades. In the southeast, fires in 2001-02 2002-03, 2005-06, 2006-07 and 2008-09 burned over four million hectares across New South Wales, Victoria, south-east Queensland and the Australian Capital Territory. The toll in human terms was significant: for example, in the 2009 Victorian fires, more than 2000 buildings and 173 lives were lost, along with major losses of crops, plantations and potential yields of water in key catchments (Teague et al. 2010). The staccato of recent major outbreaks of fire in southern temperate and desert regions was accompanied by the incessant annual rhythm of fire across the vast savannas of northern Australia (average ca. 385000 km2 burned each year; from 1997-2004; Russell-Smith et al. 2007). The extent offire in the interior and tropics therefore dwarfs that which occurs in temperate regions, even in an era of major fire in the latter (Maier and Russell-Smith 2012, Chapter 4). Fires in the heavily populated temperate regions attract saturation coverage in the media, but relatively little attention has been paid to fire issues in the interior and tropics. This situation is changing due to new management initiatives in northern Australia (Cook et al. 2012, Chapter 14; Williams et al. 2012, Chapter 13).

Keywords

future, fire, perspectives, ecosystems, regimes, australian, enduring, questions, management

Disciplines

Medicine and Health Sciences | Social and Behavioral Sciences

Publication Details

Bradstock, R. A., Williams, R. J. & Gill, A. Malcolm. (2012). Future fire regimes of Australian ecosystems: new perspectives on enduring questions of management. In R. A. Bradstock, A. Malcolm. Gill & R. J. Williams (Eds.), Flammable Australia: Fire Regimes, Biodiversity and Ecosystems in a Changing World (pp. 307-324). Collingwood, Vic: CSIRO Publishing.

Future fire regimes of Australian ecosystems: new perspectives on enduring questions of management.

R.A. Bradstock[1], R.J. Williams[2] and A.M. Gill[3,4]

[1] Centre for Environmental Risk Management of Bushfires, Institute for Conservation Biology and Environmental Management, University of Wollongong, NSW 2522, Australia.

[2] CSIRO Sustainable Ecosystems, CSIRO Climate Adaptation Flagship and CSIRO Sustainable Agriculture Flagship, Tropical Ecosystems Research Centre PMB 44 Winnellie NT 0820, Australia.

[3] The Fenner School of Environment and Society, Linnaeus Way (Building 48), College of Medicine, Biology & Environment, The Australian National University, Canberra, ACT 0200, Australia.

[4] Bushfire CRC, 340 Albert St, East Melbourne, Victoria 3002, Australia.

Abstract

There is heightened interest in fire management in Australia due to recent major fires in the south, new initiatives in the north and the influence of climatic change. Major inquiries, changes to land tenure and use, and the make-up of fire agencies have raised

Formatted

the level of interest in fire management and its scientific underpinnings. Management must address a more diverse range of needs (e.g. human protection, biodiversity conservation, water quality and amount, smoke, greenhouse gas emissions, carbon dynamics). New insights ranging from the evolutionary ecology of fire, connections between past climatic change and fire activity, to technologies for viewing and analysing large-scale fire patterns are altering the way we view and understand Australian fire regimes and their ecological consequences. New global perspectives on fire and the need to comprehend and mitigate the effects of rapid climate change are also transforming these disciplines. Nonetheless, the degree to which we can modify fire regimes to suit management needs remains uncertain (e.g. fire regimes may be only partially manipulated). Progress in managing fire regimes for biodiversity conservation in particular will depend on a significant transformation in knowledge of key biotic responses at multiple scales (local to global). Unprecedented opportunities now exist to achieve this.

Introduction

This book provides a contemporary overview of the state of knowledge of fire as a shaper of biodiversity and ecosystems in Australia, along with insights into the way in which a “Flammable Australia” may fare under future climate change. It comes at the end of a decade (2000 to 2010) of extraordinary fire activity in Australia, matched by heightened public interest in fire and debate about its management.

The decade commenced with major fire activity between 2000 and 2002 in the central and north western deserts (Nano *et al.*, this volume), at scales not seen in decades. In the south east, fires in 2001/2 2002/3, 2005/6, 2006/7 and 2008/9 burned over four million hectares across New South Wales, Victoria, south east Queensland and the Australian Capital Territory. The toll in human terms was significant: for example, in the 2009 Victorian fires, more than 2000 buildings and 173 lives were lost, along with major losses of crops, plantations and potential yields of water in key catchments (Teague *et al.* 2010). The staccato of recent major outbreaks of fire in southern temperate and desert regions, was accompanied by the incessant annual rhythm of fire across the vast savannas of northern Australia (average ca. 385,000 km^2 burned p.a.; from 1997-2004; Russell-Smith *et al.* 2007). The extent of fire in the interior and tropics therefore dwarfs that which occurs in temperate regions, even in an era of major fire in the latter case (Maier and Russell-Smith this volume). Fires in the heavily populated temperate regions attract saturation coverage in the media, but relatively little attention has been paid to fire issues in the interior and tropics. This situation is changing due to new management initiatives in northern Australia (Cook *et al.*; Williams *et al.*, this volume).

The past decade has been influential in stimulating new research funding and activity in Australia, as well as providing grist for the mill of new research. One key thematic question from the decade is enduring: what causes major fires, particularly those with socially disastrous consequences? Attempts to answer this fundamental question involve a mixture of new and old perspectives and changes in scientific emphases.

Recent major fires in the forests and woodlands of the south coincided with severe and prolonged drought, as in the past (Esplin *et al.* 2003; Ellis *et al.* 2004, Bradstock 2008). In contrast to the past, however, links with climate change have been commonly invoked to explain the occurrence of fires in the 'new millennium'. Such fires, their surrounding circumstances and effects are seen as a harbinger of things to come under a rapidly warming and drying climate, or else a direct result of it. Such claims have changed the dynamics of debate about another enduring question: to what extent can we control or domesticate fire in order to influence fire regimes (Gill, this volume)? This question lies at the core of management, particularly where vulnerable economic, social and environmental assets are at stake.

Solutions for many enduring problems of management appear to be elusive on the one hand, yet, on the other, the science of studying fire and its influences on ecosystems has entered its most rapid period of development. New global perspectives on fire are quickly emerging that have the potential to fundamentally alter the way we regard fire. The last decade may be best labelled as "the decade of global fire" not only because of the large amount of area burned in prominent fire seasons in many continents (Williams and Bradstock 2008) but also because of the development of new perspectives on measuring, modelling and understanding fire regimes and their consequences.

Here we highlight future challenges in managing fire and its interactions with the unique biota of the continent, under a changing climate in particular. We foreshadow the way that enduring questions may be further addressed, using the themes and directions highlighted in the preceding chapters. Specifically we ask:

- How is the content and underlying socio-political context of fire management changing and diversifying?
- How can we address the challenges of the future through understanding the past?
- What are the wider consequences of and opportunities provided by new ways of seeing and measuring fires?
- Can we control or subdue unplanned fires through active or managed use of fire?
- What developments are needed to heighten our capacity to manage fire regimes and their effects on biodiversity, given future global change?

In addressing these questions, we emphasize that while there is much more to know about fire, the opportunities for us to learn and live with fire in a rapidly changing world are unprecedented.

The changing 'realpolitik' of fire

The past decade has seen a remarkable level of review and debate about the management of fire. In Australia, 'the decade of fire' may be synonymous with the 'decade of fire inquiries' and intense media scrutiny, particularly in southern Australia. This includes national inquiries (e.g.Ellis *et al.* 2004) along with major inquiries held in State jurisdictions (e.g. Esplin *et al.* 2003). These culminated in the 2009 Victorian Bushfires Royal Commission (Teague *et al.* 2010), which has had national and international ramifications (e.g. Mutch *et al.* 2011; Gill and Cary in review) for fire management and research. This decade also saw the emergence of large-scale litigation concerning management of fires and their effects.

While such a level of introspection is understandable given the toll of human lives and property in the decade, will major changes to fire management policies and practices result? What are the implications for management of biodiversity and ecological processes?

Scrutiny of fire is more intense than ever because of heightened coverage by media. Much of the treatment of fire management issues by the mainstream media is shaped by the search for controversy and to apportion blame, rather than an exploration of the complexity of and background to the problem. For example, there is a tendency to label each major fire as the “worst in history”. Fires are still commonly reported as “destroying” vegetation. As with other natural disasters involving extreme climatic phenomena, climate change is sometimes invoked as the cause, despite the practical difficulties in testing such a proposition.

Coupled with these changes in public scrutiny and perception are changes to the way fires are managed. Throughout much of the nation, planning and operations were dominated by professional land and natural resource managers (e.g. forestry and conservation agency staff) supplemented by volunteers. Now, the burden of responsibility for fire management is being increasingly shouldered by emergency services bureaucracies whose principal obligations are to protect life and property. This creates a potential tension between land management and human protection obligations that is reflected in public debate and commentary.

The trend toward centralized control of decision-making in fire management is postulated to result in disengagement from local communities and issues and may sub-ordinate the importance of land management objectives and issues and the input of relevant expertise. Conversely, when fire is actively used for human protection purposes, adjacent to major population centres, the ensuing smoke can cause controversy due to air quality and human health concerns, negative effects on horticulture and tourism, and temporary road closures. Wider appreciation of the complex web of implications and responsibilities implicit in the contemporary and future fire management portfolio is required. Managers not only face these dilemmas but also the growing demands of the public in general to be informed about fires and the gamut of their consequences on humans and the environment. Major fires, such as those in Victoria in early 2009, have generated heightened expectations and demands for accurate and timely warnings and effective procedures for *in situ* protection or mass evacuation of communities. Do these trends lessen rather than strengthening our ability to comprehend and co-exist with fire? Do they enhance our ability to understand and manage the wider consequences of fire in ecological systems?

Ecological science and its applications are not divorced from the wider context of changes in social attitudes and approaches. Much of the recent discourse about the management of fire to conserve environmental values has been shaped by political battles over the management of land. Conversion of state-owned production forests into conservation reserves, controls on the clearing of native vegetation for agriculture and other developments and endangered species legislation, have created tension between proponents with economic and cultural interest in these pursuits and other elements of society seeking sustainability in land use and development. Fire, a process often associated in the public mind with intact tracts of native vegetation, has therefore been depicted as something that has been exacerbated by these land use decisions.

Political claims made in debate often neglect or distort evidence. For example, the major fires of the new millennium in southern Australia are not unprecedented in recent history in terms of intensity (Esplin *et al.* 2003; Ellis *et al.* 2004), loss of material assets (e.g. McAneney *et al.* 2009), nor in terms of associated weather conditions (Esplin *et al.* 2003; Hasson *et al.* 2009), contrary to claims sometimes made in public debate. It is a challenging task to disentangle land use effects from the plethora of key environmental factors that surround major outbreaks of fire. These examples emphasize the need and demand for an improved basis of evidence on which management decisions can be predicated. Managers, of whatever type, have a stake in building this edifice by engaging in detailed, active monitoring of fire and ecological consequences.

Many of the changes and tensions described above are driven by the management context of southern forested and agricultural regions, where the bulk of the population resides. The situation in much of the interior and north of continent is different (e.g.

sparse populations, pastoralism and extensive Indigenous land tenure) and new themes are emerging as a result. In part these are driven by not only the regular nature of fire but also the opportunities that emerge from the vast scales of these landscapes. Prominent initiatives include active fire mapping over vast areas to assist land-holders (Maier and Russell-Smith this volume) and the re-engagement of indigenous people in fire management (Cook *et al.*, this volume). This momentum stems from restoration of land rights in general and more recently the restitution of title over public land such as conservation reserves to Indigenous owners. In tropical savannas the alignment of biodiversity conservation and greenhouse gas mitigation initiatives (Cook *et al.*, this volume), has attracted national attention. However, the social circumstances surrounding such initiatives may vary strongly from place to place. In addition, the environmental context will place constraints on what fire management can achieve in terms of revenue and employment. In the future we expect greater cross-fertilization between management trends and innovations from the heavily populated but less frequently burnt south and the sparsely populated north and interior. This will flow as a consequence of shifting populations and emergence of new imperatives (e.g. carbon pricing).

Political and social changes mean that ownership of fire and its consequences is changing (i.e. those who "own" a fire will also own its consequences). Aspirations need to be tempered by this reality. Despite the changes in the social and political context of fire outlined here, important aspects endure, such as the desire to control, subdue or domesticate fire (e.g. Gill, this volume). These remain inherent to the initiatives in management that are emerging

Diversification of the fire management portfolio

Protection of lives and material assets has been the well established priority in fire management along with biodiversity conservation (Gill 2008; Driscoll *et al.* 2010). This emphasis on biodiversity reflects high levels of endemic diversity in many fire-prone ecosystems in Australia as well as statutory initiatives for the conservation of biodiversity, including the establishment of a comprehensive national reserve system. Recently, prolonged drought and associated major fires through much of southern Australia have raised awareness about the effects of fire on water resources (Gill, this volume). Similar concerns about smoke and air quality, the carbon status of terrestrial vegetation (natural and planted) and greenhouse gas emissions from fires have risen to prominence on the management agenda (Gill; Williams *et al.*; Cook *et al.*, this volume). Management is therefore more complex than ever. Can one approach to fire management serve all these objectives or does it now require much greater nuance?

The answer, in part, depends on the fundamental nature of fire regimes and the way they are affected by management. It also depends strongly on ecological responses to fires, including potential changes to the composition, structure and diversity of communities in response to varying fire regimes. Ultimately, to understand how differing fire regimes will affect other ecosystem attributes such as biodiversity, water, smoke, greenhouse gas emissions and carbon dynamics, a basic understanding of the effects of fire regimes on the dynamics of plant species and communities is required (e.g. Williams *et al.* this volume).

For example, discussion of fire and water yields has long been dominated by the model developed for cool, moist Mountain Ash (*Eucalyptus regnans*) dominated catchments in the Central Victorian Highland (Vertessy *et al.* 2001). This model predicts that water yield declines in the decades following fire, compared with pre-fire levels. Following this decline a gradual rise in yield to pre-fire levels is attained after > 100 years. This trajectory of response reflects the unique pattern of regeneration and recovery of the dominant obligate seeder *E. regnans* in these forested catchments: i.e. high water use of young rapidly growing trees following post-fire establishment.

Wide ranging discussion of fire management to suit water yield requirements has been predicated on the generality of this model of water yield. However, the bulk of forested catchments in temperate regions of Australia are dominated by resprouting eucalypts. Post-fire recovery and growth trajectories in such forests therefore differ from those in Mountain Ash-dominated catchments (Gill, this volume), and hence water yields following major fires can also be expected to differ. This may explain why studies in other eucalypt forest catchments have either shown no decline in post-fire water yields (White *et al.* 2006) or differing trajectories of post-fire decline (Lane *et al.* 2010). Potentially, a switch in fire regimes (i.e. a short interval between successive fires) leading to a decrease in *E. regnans* cover is likely to alter catchment yields. A similar scenario will apply to carbon dynamics in these forests, where a switch from obligate seeder "ash-type" dominants to resprouters will have major implications, because in the latter case, the bulk of above-ground carbon may be conserved across cycles of fire (Williams *et al.*, this volume). The evaluation of fire management options to suit these important assets is interdependent with, rather than being independent of, potential responses of plant communities and constituent species.

The future is written in the past?

What can the past tell us about managing the future? Fire is a phenomenon of deep antiquity that has developed in concert with the evolution of terrestrial vegetation (Bowman *et al.*, 2009, Bond and Scott 2010). It is therefore implausible that fire has not acted, in interaction with other factors, as a selective evolutionary force. As illustrated by Bowman *et al.* (this volume), recent analyses in quintessential Australian plant genera provide evidence that key resilience traits (e.g. serotiny, epicormic resprouting) exhibit phylogenetic patterns that are consistent with the hypothesis of a sustained selective influence of fire throughout the Tertiary. Nonetheless the idea that fire has been a major evolutionary force has struggled to gain acceptance (e.g. Bradshaw *et al.* 2011) compared with established theories concerning the influences of aridity and infertility.

While there is some recognition that evolutionary selection may involve interactions among these factors, including fire (Bradshaw *et al.* 2011), detailed discussion of how this may occur is lacking. For example, fire acts directly to reinforce infertility through losses of nutrients via volatilization, leaching and erosion (Certini

2005; Shakesby *et al.* 2007). Thus trends toward increased fire driven partly by changes to climate (e.g. increasing frequency of dry spells in moist habitats) may reinforce or exacerbate infertility. Development of more comprehensive theories concerning the coupled influences of fire, aridity and infertility on trait selection may offer a more satisfying and nuanced understanding of the evolution of flammable ecosystems (Mucina & Wardell-Johnson 2011; Keeley *et al.* in press a). In a similar vein, Bowman *et al.* (this volume) have noted the limitations of flammability theory, which hinder development of more comprehensive explanations of the role of fire in driving evolutionary and ecological dynamics. Part of the challenge is to develop theory that accommodates the coupled influences of plant species traits (e.g. resilience and flammability) and their mediation by external factors (e.g. effects of moisture on habitat availability) that are linked to climate and soils. Ultimately, competitively 'superior' flammable species can dominate ecosystems when available patches of habitat are sufficiently large and interlinked to allow emergent fire regimes to become predominant across entire landscapes (Keeley *et al.* in press a). The theoretical interplay between climate, fire weather, flammability, habitat availability and resilience awaits more formal integration, yet such a development may be needed to more completely understand the implications of rapid climatic change.

What role will a more complete understanding of the evolutionary influence of fire provide to future managers of ecosystems? In their recent review, Bradshaw *et al.* (2011, argued against the notion of fire as an evolutionary force, in part to counter the contemporary use of the slogan "fire adapted" as a justification for use of frequent prescribed burning as a management technique in ecosystems with high plant diversity. In essence this recapitulates an old debate that, in part, led to the development of the fire regime concept (i.e. plants are not adapted fire *per se*, but to fire regimes Gill 1975, 1981). Thus, the argument about the influence of fire in shaping the evolution of traits that confer resilience to fire may be largely irrelevant in a management sense (Keeley *et al.* in press b).

The use of traits to evaluate and classify species into functional types that demarcate differential responses to components of the fire regime (Keith this volume) has developed to the point where trait-based systems are now commonly used in fire management within Australia (e.g. Bradstock and Kenny 2003; Burrows 2008; Edwards and Russell-Smith 2009; Keith this volume). Further research on the evolutionary provenance of putative "fire-adaptive" traits may serve no purpose other than to stiffen the moral authority for use of detailed information on species attributes in fire management. Perhaps the wheel has turned full circle: the impetus is now to develop new evolutionary perspectives that account for the well-documented intricacies of fire regimes and ecological response traits.

Kershaw *et al.* (2002) provided new perspectives on changes to fire through the Holocene across southern Australia, based on a meta-analysis of sedimentary charcoal data. This overview indicated that fire activity generally accelerated over the last two hundred years and then declined later in the European era. New meta-analyses (Mooney *et al.*, 2010; Mooney *et al.*, this volume) also exhibit this trend, using a wider range of

Australasian data. There is resonance between these studies and other recent global analyses (Marlon et al 2008; Mooney *et al.* this volume). These wide-ranging studies infer a tight coupling between fire, atmospheric temperatures and CO_2 concentrations that have only recently (i.e. last 200 years) been disrupted in mid-latitude regions by widespread clearing for agriculture. This suggests that future fire activity will generally increase under climate change, and human management interventions (i.e. prevention and suppression activities), aside from widespread land clearing, may have little potential to alter fire regimes.

Alternatively, Cary *et al.* (this volume) argue that fire activity may decline as a function of future warming and drying trends over much of Australia, due to constraints on growth of herbaceous fuels. Empirical, positive correlations between area burned and rainfall in arid Australia (Allan and Southgate 2002; Nano *et al.*, this volume) lend support to this conclusion. In a similar vein, Bowman *et al.* (this volume) postulate that Aboriginal people had major effects on the nature of fire regimes, through presumed influences on fuel via planned use of fire in various ecosystems. This theme is echoed in contemporary and future management initiatives in tropical savannas (Cook *et al.*, this volume).

Perspectives from the past on the relative influences of humans and climate on fire are therefore not unequivocal when judged against other lines of evidence. Is it possible to resolve the divergent conclusions posed by differing types of evidence, particularly in relation to the enduring questions about our role in managing a wide array of intrinsically flammable ecosystems?

Fire regimes - the new 'vision splendid'

Methods for measuring fire regimes are developing rapidly due to the use of widely available data from remote sensing (Maier and Russell-Smith this volume) and the analytical capabilities of Geographic Information Systems. Matching developments in statistical approaches for dealing with such data (e.g. Murphy *et al.* 2011) mean that there is a greatly enhanced capacity to explore patterns of fire regimes and their influence. Fundamentally these developments provide the opportunities to explore patterns and processes of fire at spatial and temporal scales beyond the level of plots and summaries of annual area burned. Valuable insights have been developed on the basis of these methods, and the opportunities to directly measure and analyse the determinants of fire activity, resultant fire regime patterns and their effects at multiple temporal and spatial scales are unprecedented. This capability can revolutionize the way we understand and manage fire regimes.

Much of our understanding of the behaviour of fires (Sullivan *et al.*, this volume) is based on small-scale experiments in either the laboratory or field (Sullivan 2009). While modelling has been used to extrapolate this knowledge to large spatial scales and to incorporate complex interactions between fire and the atmosphere (e.g. Mell *et al.* 2007), fire behaviour science is largely a "bottom-up" process of extrapolation from a small-scale experimental base. Models remain largely untested at spatial and temporal scales that are relevant to management and to full examination of effects on biodiversity and the functioning of ecosystems. New ways of seeing fire offer the potential to overcome this limitation. For example, satellite-based methods of estimating fire severity (i.e. vertical profiles of biomass loss/damage, Keeley 2009, or measures of fire radiative power, Maier and Russell-Smith, this volume) provide a way of assessing fire intensity patterns in time and space. Such insights, in local forests (e.g. Bradstock *et al.* 2010) are consistent with the likely under-prediction of rate of spread of fire behaviour models under severe weather conditions (Sullivan and McCaw 2009). The development of remotely-sensed methods for progressive mapping of active fire lines provides more accurate data for studying fire behaviour, spread and intensity characteristics in relation to abroad range of environmental variation.

The development of continental- and global-scale mapping of fire patterns not only provides a way of measuring large-scale variations in fire regimes but also insights into their determinants. For example, Russell-Smith *et al.* (2007) provided an overview of contemporary fire patterns in Australia, that not only highlights the dominant role of fire in the tropical north but also the likely effect of pastoral and agricultural activity in subduing fire over the eastern interior of the continent. Global perspectives on contemporary fire derived from remote sensing not only document the “non-linear” nature of the relationship between fire and environmental factors such as available moisture (Mooney *et al.*; Cary *et al.* this volume) but also the influences of human populations and land use (e.g. Krawchuk *et al.* 2009).

Cross-continental comparisons afforded by remotely sensed data on fire and vegetation patterns offer the potential to forge new ecological generalities. Where does Australia stand in the world of fire? Are the attributes of local biota and associated fire regimes in individual Australian ecosystems necessarily unique, compared with comparable ecosystems elsewhere? For example, a cross-continental comparison of the environmental correlates governing the distribution of tropical savannas in Africa, Australia and South America indicates broad similarities but also divergences in the distribution of these highly fire-prone ecosystems (Lehman *et al.* 2011). The influence of *Eucalyptus,* as a highly flammable dominant may be responsible for allowing Australian savannas to occupy the wetter end of the moisture gradient in tropical landscapes compared to other continents, thereby usurping closed forests (Lehman *et al.* 2011). The high resilience of eucalypts, through various modes of rapid resprouting, confers a further synergistic advantage in this regard (Lehman *et al.* 2011; Bowman *et al.* this volume). Thus global perspectives on the joint distributions of fire and vegetation suggest that Australian savannas exhibit variations on a universal pattern.

Much scope exists to more formally explore comparative trends globally across other biomes. For example, how influential are eucalypts in determining the fire regimes and distributional limits of temperate forests and shrublands? Comparisons of this kind, driven in part by the imperative to understand the role of fire in mediating biosphere–atmosphere interactions, will shed further light on the way in which fire acts, the degree to which human interventions can alter fire regimes and the future of the unique biota of the continent. New ways of seeing fire make this possible.

Leveraging the future

New insights into the manipulation of fire regimes via prescribed burning provide key information about potential future management strategies. Prescribed burning remains the predominant method for treating fuel in Australia. Such treatment potentially reduces the incidence, rate of spread and intensity of unplanned fires and consequent risks to people and ecological attributes. Recent modelling and empirical studies indicate that the long-term relationship between rates of unplanned fire and rates of treatment varies systematically across ecosystems (Bradstock and Williams 2009; Bradstock *et al.* in review; Williams *et al.* this volume). In particular the ratio of reduction of average area of unplanned fire to average area treated (prescribed fire) is a useful metric of management "effectiveness" that is relevant across large spatial and temporal scales. This ratio has been termed "leverage". As such, it is complementary to other metrics such as "hazard" functions which can be used to evaluate the relative strength of weather and fuel effects on probability of burning across landscapes (McCarthy *et al.* 2001). Muted responses of burning probability to time since fire have been postulated to indicate that fuel treatment effects may be restricted in some landscapes by the influence of severe weather (Moritz *et al.* 2004; van Wilgen *et al.* 2010).

Measures of leverage provide insight into the way fire regimes and ecological responses vary a across and among ecosystems according to differing treatment regimes. Where the average substitution of area burned by unplanned fires by area of prescribed fire is partial (i.e. to eliminate one hectare of unplanned fire multiple hectares of prescribed fire are required), the overall area burned (i.e. sum of prescribed and unplanned fire) and frequency of fire will increase with increasing rate of treatment (e.g. King *et al.* 2006). Under such a scenario of low leverage, average length of inter-fire interval and average fire intensity will therefore tend to decline. Such a scenario appears to apply for eucalypt forests, where an average of three or four hectares is required to reduce a hectare of unplanned fire (Boer *et al.* 2009; Price and Bradstock 2011). By contrast, in tropical savannas, the ratio of input of prescribed fire to reduction in unplanned fire area is about unity (i.e. high leverage). Accordingly, as rate of treatment increases area burned and average length of inter-fire interval may remain constant, whereas average fire intensity will tend to decline.

The implications of these trends in fire interval as a function of differing levels of "effectiveness" of prescribed burning are varied. At low leverage, the decrease in inter-fire interval that results from increasing rates of treatment may negatively affect biota that are sensitive to the length of inter-fire interval (i.e. interval-sensitive species, Bradstock 2008) such as woody obligate seeders (Keith, this volume). By contrast, biota that are sensitive to fire intensity (intensity-sensitive species), such as arboreal mammals and birds with restricted flight (Gill, this volume) will tend to be advantaged by increasing rates of treatment if leverage is low. Such trends may be identified for other ecosystem responses that underpin alternative management ‘values’. For example, carbon losses in emissions may tend to increase with increasing treatment rate at low leverage but decrease when leverage is high (Bradstock and Williams 2009; Bradstock *et al.* in review; Williams *et al.*, this volume). Volumes of smoke and subsequent effects on air quality and human health may follow similar trends.

The metric of management effectiveness provided by leverage not only opens the pathway to a more formal understanding of how fire regimes may differentially respond to management but also provides the key to perhaps the most fundamental conundrum, namely the extent, spatially and temporally, to which fire regimes can be manipulated. As we have indicated above, differing lines of evidence offer contrary conclusions in this regard.

The implications of ‘effectiveness’, as defined in leverage, lead readily to a consideration of cost and feasibility of implementation. How much management intervention is feasible given the magnitude of the problem (e.g. area of fire prone land) on the one hand and resources on the other? What level of influence is currently exerted through management and what level is desired? Is it possible to eliminate large, intense fires that are deleterious to human communities? Would it be desirable to do this in an ecological sense? Where leverage is relatively low, as in temperate eucalypt forests, current rates of prescribed burning in some regions (e.g. 1 to 2% area treated per annum in south eastern Australia) are most likely to have only small effects on the incidence and area burned by unplanned fire. Substantial increases in rate of treatment (e.g. 5% area treated p.a.) have been recommended for Victoria (Teague *et al.* 2010) and elsewhere as a result. While such recommendations have been embraced by governments, the ramifications of cost-effectiveness remain elusive. Such a rate of treatment may result in a diminution of various measures of unplanned fire (e.g. average area burned by unplanned fire, Boer *et al.*, 2009; Price and Bradstock 2011) but the risk they pose to human communities may remain substantial. Whether such residual risk (Esplin *et al.*, 2003) is acceptable in a political or social sense is unknown. Cost constraints alone may mean that the influence of management on fire activity will at best be partial rather than total in these environments.

Initiatives for intensive treatment and modification of vegetation around built assets, while already in practice (e.g. Gill and Stephens 2009), may be supplemented by other measures such as improved planning and construction standards for buildings and increased householder suppression capacity (Gill 2009) in the future. Such approaches are defensive by nature, in that they seek to reduce direct impacts of major fires on human communities. The emphasis in this case is on local rather than regional or global control of fire. Perhaps this is the logical conclusion that may be drawn from the emerging body of empirical evidence about management influences. The scale of the problem is such that control over unplanned fire activity is only ever likely to be partial or at least focused in some landscapes, or parts thereof, but not others. Such activities, no matter how effective, are superimposed on the influences of other biophysical drivers of fire.

Humans have partially altered climatically-driven fire signals to varying degrees, in time and space in the past, but the relative strength of climatic drivers may have obscured or masked these effects. For example, Bradstock *et al.* (2008), show that effects of an increase in rate of prescribed burning from current levels (circa. 1%) to 5 % per annum may be negated by the effects of projected 2050 climate change (i.e. increase in severity of fire weather) in dry eucalypt forests. Irrespective of the level of prescribed fire in this instance, fire activity is predicted to increase. Prescribed burning may partially modulate the level of increase. Such insights reinforce the need to understand the scope and limitations of potential management intervention in the future.

Managing for biodiversity: the *Don Quixote* factor

Has progress been made in managing fire for the conservation of biodiversity? As with the mythical knight, is it a perpetual exercise in 'tilting at windmills'? Have advances in understanding biotic responses to fire regimes had an influence on fire management? In turn, are the challenges and uncertainties of management stimulating a research agenda that will lead to significant advances in management capacity and effectiveness?

Currently, management of fire regimes for biodiversity conservation reflects ongoing interplay and tension between two paradigms concerning, respectively, "mosaics" and "functional types". In turn, the tension between these paradigms reflects contrasting advances and seemingly recalcitrant deficiencies in concepts and knowledge. Thus the state of play in both management and underpinning research involves unresolved paradoxes and tensions that are reflected both within and among the chapters in this book.

The desire to manage for mosaics reflects an intuitive assumption that fire intensity is paramount as a factor that determines ecological response, particularly the notion that high intensity fires will be lethal to organisms, especially larger animals (Bradstock *et al.* 2005; Bradstock 2008; Clarke 2008). It also reflects assumptions that differing organisms depend on differing quasi-successional, post-fire age classes (Bradstock *et al.* 2005). In contrast, the impetus to manage for 'sensitive functional types' depends on the concept of fire as a recurrent disturbance. The life cycles of species need to mesh with cycles of fire if species are to persist (Gill 1975). Formal categories of "functional types" based on coupled syndromes of traits, particularly in plants, were largely developed in response to this concept (Keith this volume). Thus the two paradigms emphasize differing aspects of the fire regime (i.e. fire intensity versus fire frequency) and differing dimensions in time (i.e. time since fire versus time between fires or length of inter-fire interval).

As noted, management systems that utilize plant traits and functional types are now commonplace in Australia. By and large these attempt to predict desirable domains of length of inter-fire interval (fire frequency envelopes), often for broad vegetation groupings. Such initiatives constitute a "bottom-up" approach to prediction of ecological responses to fire regimes. They have been developed chiefly using meta-analyses of plant attributes, derived from mixtures of sources (Bradstock & Kenny 2003; Edwards and

Russell-Smith 2009; Vivian *et al.* 2010) with the intention to form part of an adaptive approach to fire management.

While trait based approaches to define “thresholds of potential concern” (Van Wilgen 2009; Keith, this volume) for length of inter-fire interval have risen to prominence in the last decade, a number of management jurisdictions continue to aim to manage for “mosaics”(i.e. spatial heterogeneity of burning patterns; see Gill 2008), particularly through the use of prescribed fire. Contrary to initiatives that define desirable domains of inter-fire interval, formal, quantitative guidelines for mosaics based on ecological attributes of species are lacking, though some jurisdictions attempt to specify criteria for percentage area to be burnt within areas treated with fire. In isolation, the term “mosaics” is inadequate as a descriptor because mosaics consist of patches which vary in size, shape and dispersion (Gill 2008; Gill and Allan 2008). All fires create mosaics of some kind, and many different types are possible. Insights are lacking as to which type of mosaic is desirable in terms of particular biota. The requirements of co-habiting species ranging from invertebrates to vascular plants are unlikely to be the same, as indicated in a range of chapters in this book.

Both paradigms have other important limitations. Evidence suggests that many groups of plants and animals are relatively insensitive to fire intensity variations (e.g. Nano *et al.*; Enright *et al.*;Fensham *et al.*. this volume) or else recover quickly from intense fires (York *et al.*. this volume), just as many groups of plants may be largely insensitive to variations in fire frequency. Evidence that animal taxa depend on any particular post-fire stage or age class is lacking, though species may show peaks in abundance at certain times (Driscoll *et al.* 2010; Enright *et al.*; Nano *et al.*; York *et al.* this volume). Tractable schemes for classifying animal responses to differing fire regime components are also lacking (Keith, this volume) though frameworks have been suggested (Bradstock *et al.* 2005). Schemes for classifying plant responses to fire based on relatively simple life history attributes (Gill 1981, Noble and Slatyer 1981, Pausas *et al.* 2004) need to be integrated with other schemes that classify species on the basis of functional and morphological traits (Katge *et al.* in press).

While many current management policies and plans aim to create mosaics as well as to manage for a desirable range of inter-fire intervals, the inherent linkages between these paradigms are often not recognized or articulated, despite available explorations of their formal interconnection (McCarthy *et al.* 2001; Bradstock *et al.* 2005). While it is often assumed that the fire regimes required to suit certain plant groups will favour animal taxa, such assumptions remain largely untested (Clarke 2008), though linkages between plant population and community structure and animal habitats are critical, as demonstrated in various chapters here. A default position often invoked in management is that spatial heterogeneity of individual fire patterns will save the day. Such an assumption is implicit in the nostrum “pyrodiversity favours biodiversity” (Parr and Andersen 2006; van Wilgen 2009). Accordingly, it is assumed that there will always be patches in the landscape which miss certain fires, thereby providing refugia for taxa that may be sensitive to short intervals between fire. This assumption has been criticized in various ways (Driscoll *et al.* 2010): specifically, it neglects the issue of the quantity (i.e. area) and configuration of patches of differing burn or fire interval status needed to sustain dependent species, particularly those which may require long-unburnt and infrequently burnt habitat (e.g. Nano *et al.*, Enright *et al.* this volume).

The dearth of quantitative criteria for defining optimal ranges of mosaics (e.g. size, shape and configuration of patches) reflects the lack of formal evidence linking heterogeneity of fire patterns to ecological responses (Parr and Andersen 2006; Driscoll *et al.* 2010). Contrasts in chapters within this book illustrate this problem: on the one hand Bowman *et al.* (this volume) hypothesize that declines of fauna during the European era in tropical savannas and arid regions, are in part due to reduced heterogeneity of fires, whereas Fensham (this volume) and Nano *et al.* (this volume) respectively claim that resident biota are either relatively insensitive to variations in fire regimes or that other factors such as exotic predators are responsible for recent declines in abundance. The data needed to distinguish between these alternatives is lacking. Similarly, there are few data that specify levels of critical fire intensity for susceptible biota such as larger mammals, though some can be inferred (Gill, this volume).

Fire management arguably awaits development of a stronger research base that more clearly integrates these paradigms. The following recommendations may be useful in this regard, particularly in environments that may be rapidly changing due to climatic and human influences.

First, there is a need to improve our understanding of responses of biota (animals in particular), to spatio-temporal patterns of fire regime components at varying scales (e.g. points, patches, landscapes, regions). Opportunities now exist to document such patterns (see above), and to utilize such opportunities to design and analyse “natural experiments” across regional scales (e.g. Haslem *et al.* 2011; Faivre *et al.* 2011; Murphy *et al.* 2011). In particular there is a need to jointly consider both the visible (i.e. fire-patch demography; Gill *et al.* 2003) and invisible mosaics (inter-fire interval variation) as coupled influences on biota (Gill *et al.* 2003; Bradstock *et al.* 2005; Parr and Andersen 2006). “Pyrodiversity” has many facets: an understanding of spatio-temporal variation of all fire regime components is required to give full meaning to this term. The“mosaic” and functional type paradigms are ultimately differing sides of the same coin.

Such insights will depend on the development of a comprehensive atlas of fire maps, in effect a national, spatial fire chronology. Such a resource, the foundation for the simplest level of understanding of fire regimes (i.e. fire intervals), needs to be supplemented with information about fire severity, as a surrogate for fire intensity (Keeley 2009) and other relevant fire regime attributes (e.g. season of fires). Assembly and maintenance of an appropriate, national fire regime database of this kind will provide an ongoing basis for exploration of biotic and ecological responses that can be used not only to provide for development of general principles but also to directly monitor changes to fire regimes and biota in response to global change.

Development of trait-based approaches to fire management have possibly reached an impasse which cannot be breached without acquiring a much larger body of empirical data or a change in approach such as classifying species' characteristics that determine responses to all components of the fire regimes, not just interval (Gill and Stephens 2009).

Second, a more nuanced appreciation is required of the relative sensitivity of responses of biodiversity to fire regimes at within- and between- community scales. Fluxes in a few species may be large, and have large effects on other species, in some communities but not others. Considerations of resource availability and competitive interactions need to be engineered into an overview of fire. While relevant theories exist (e.g. Clarke *et al.* 2005; Pausas & Bradstock 2007; Lunt *et al.*, this volume), application and testing of these theories is limited. Global change will affect these resources and a more complete understanding of the consequences of such changes (e.g. altered resilience) is required to comprehend the possibilities. Similarly, how much spatial heterogeneity needs to be engineered into the fire regime, as opposed to what emerges from influences such as variations in weather and terrain (e.g. Bradstock 2008; Bradstock *et al.* 2010)? The possibility exists that some landscapes are intrinsically buffered against effects of adverse fire regimes on particular biota, because of the grain of their inherent heterogeneity (e.g. Faivre *et al.* 2011).

Third, the challenge of understanding the effects of climate change not only involves development of predictions of change to fire regimes (i.e. changes to the frequency, intensity, season and type of fires) but also the implications of the interaction between changing fire regimes and environments for biodiversity and ecological processes. The influence of changed levels of moisture, temperature and CO_2 will strongly affect biota in the interval between fires through effects on regeneration, growth and reproduction. Such effects will interact with the direct effects of changes in fire regimes. For example, "interval squeeze" induced by lower moisture under climate change has the potential to cause major changes to species and vegetation composition via the combined effects of shorter length of inter-fire intervals and slower rates of growth and reproduction (e.g. longer juvenile periods, lower seedling survival rates and lower seed production and seedbank accumulation (Williams *et al.* 2009; Enright *et al.*, this volume). Such a possibility reinforces not only the necessity to understand effects and interactions of fire regimes and biodiversity *per se*, but also the need to widen the focus to include a deeper functional understanding of the interplay between fire regimes, variability in resources, climates and resulting biotic responses.

Fourth, the 'realpolitik' of fire increasingly demands a more detailed evidence-base on which policies and practices can be predicated. Evidence devoid of context can be misleading because there are ecological limits to applicability. A systematic understanding of the environmental determinants of ecological response syndromes is critical to this task. Lunt *et al.* and Nano *et al.* (this volume) illustrate examples in this regard. Without an understanding of how responses to fire regimes vary along major ecological gradients there is the real possibility that incorrect and inappropriate interpretations of evidence will be made. A systematic appraisal of such macro-variations in ecological responses is also critical for understanding implications of climatic change, particularly if comparative inference is derived from appropriately arranged studies in relation to temperature and moisture variations.

Fifth, the concept of leverage, as outlined above offers a way of resolving the disjunction between management paradigms by quantifying the interactions between prescribed and unplanned fires. A clearer understanding of the trade-offs in fire regime components involved in using fire in differing environments will allow a more targeted approach to development of management strategies. We anticipate that the insights from leverage, along with a better understanding of other fire management activities will provide the foundations for development of formal decision analyses that explore optimal solutions and trade-offs among the portfolio of fire management objectives (Driscoll *et al.* 2010; Penman *et al.* in press). Such developments will inject a much needed degree of realism and pragmatism into debates about management. Ultimately, management planning and decision-making must reflect the constraints of finite resources. Knowledge about the degree to which these resources can affect fire regimes and how differing facets of management can be best deployed to achieve such effects is critical to the future, particularly if conditions conducive to major fires become more prevalent in some ecosystems.

Like tilting at windmills, the notion of creating mosaics and hoping for the best may satisfy intuitive ideals, but may do little to meet the future demands of both fire 'realpolitik' and rapidly changing environments. Fire management is poised to make the transformation into a discipline that can more readily confront the complexities and trade-offs that are inherent to its make-up. The future demands it.

Conclusions

We have foreshadowed a transformation of fire management and its role in sustaining biological diversity and associated ecological processes. Arguably, the new insights into the enduring questions we have highlighted stem principally from broad scale syntheses of data on fire regime patterns and ecological responses derived from wide ranging sources and methodologies. Our understanding of the degree to which we can control or domesticate fire, the necessity to do so for purposes of conservation, resource management and climate change mitigation or adaptation, and, the nature of changes to fire regimes required to meet these challenges, will largely depend on our ability to further assemble a comprehensive and extensive picture of fire regime patterns across all ecosystems. New ways of viewing, measuring and mapping fire are pivotal to this task.

While the nature of responsibilities for fire management may be changing, fire research disciplines are also rapidly diversifying, in response to the challenge of global change. Traditionally, fire research was strongly centred in forestry disciplines, with a focus on development of an understanding of the physical drivers of fire behaviour. Much has changed over the last few decades with the burgeoning of research on fire ecology, including palaeo-ecological perspectives on fire (Gill *et al.* 1981; Bradstock *et al.* 2002). Social scientists, geographers, spatial and remote-sensing scientists and climate modellers, among others, are now vigorously engaged in ‘solving’ the puzzle of fire. This reflects the reality that fire is a universal, global phenomenon with fundamental ramifications for ecosystems, the atmosphere and humans. Further development of our understanding of its interplay with ecological systems must be outward looking, in order to comprehend the significance of what is happening close to home.

Acknowledgements

We are grateful to all authors of the chapters in this book for contributing to the material and ideas discussed here. The interpretations placed on their work are ours, but the stimuli belong to them. DXF Cervantes provided invaluable insights. We thank Alan Andersen and Neal Enright for invaluable reviews of the manuscript.

References

Allan GE and Southgate RI. (2002) Fire regimes of the spinifex landscapes of Australia. In *Flammable Australia: The Fire Regimes and Biodiversity of a Continent* (Eds RA Bradstock, JE Williams and AM Gill) pp. 145-176. CAMBRIDGE UNIVERSITY PRESS, Cambridge.

Boer MM, Sadler RJ, Wittkuhn RS, McCaw L and Grierson PF (2009) Long-term impacts of prescribed burning on regional extent and incidence of wildfires - evidence from 50 years of active fire management in SW Australian forests. *Forest Ecology and Management* **259**, 132-142.

Bond WJ and Scott AC (2010) Fire and the spread of flowering plants in the Cretaceous. *New Phytologist* **188**, 1137-1150.

Bowman DMJS, Murphy BP, Burrows GE, and Crisp MD Fire regimes and the evolution of the Australian biota. (This volume).

Bowman DMJS, Balch JK, Artaxo P, Bond WJ, Carlson JM, Cochrane MA, D'Antonio CM, DeFries RS, Doyle C, Harrison SP, Johnston FH, Keeley JE, Krawchuk MA, Kull

CA, Marston JB, Moritz MA, Prentice IC, Roos CI, Scott AC, Swetnam TW, van der Werf G R and Pyne SJ (2009) Fire in the Earth System. *Science* **324**, 481-484.

Bradshaw S, Dixon K, Hopper S, Lambers H and Turner S (2011) Little evidence for fire-adapted plant traits in Mediterranean climate regions. *Trends in Plant Science* **16**, 69-76.

Bradstock RA (2008) Effects of large fires on biodiversity in south-eastern Australia: disaster or template for diversity? *International Journal of Wildland Fire* **17**, 809–822.

Bradstock RA and Kenny BJ (2003) Application of plant functional traits to fire management in a conservation reserve in south-eastern Australia. *Journal of Vegetation Science* **14**, 345-354.

Bradstock RA, Williams RJ (2009) Can Australian fire regimes be managed for carbon benefits? *New Phytologist* **183**, 931–934.

Bradstock RA, Gill AM and Williams JE (Eds) (2002) *Flammable Australia: The Fire Regimes and Biodiversity of a Continent.* CAMBRIDGE UNIVERSITY PRESS, Cambridge.

Bradstock RA, Bedward M, Gill AM and Cohn JS (2005). Which mosaic? A landscape ecological approach for evaluating interactions between fire regimes, habitat and animals. *Wildlife Research* **32**, 409-423.

Bradstock R, Davies I, Price O and Cary G (2008) 'Effects of climate change on bushfire threats to biodiversity, ecosystem processes and people in the Sydney region'. Final Report to the New South Wales Department of Environment and Climate Change: Climate Change Impacts and Adaptation Research Project 050831. 72 pages.

Bradstock RA, Hammill K, Collins L, Price OF (2010) Effects of weather, fuel and terrain on fire severity in topographically diverse landscapes of south-eastern Australia. *Landscape Ecology* **25**, 607–619.

Bradstock *et al.* in review

Burrows N (2008) Linking fire ecology and fire management in south-west Australian forest landscapes. *Forest Ecology and Management* **255**, 2394-2406.

Cary GJ, Bradstock RA, Gill AM and Williams RJ Global change and fire regimes in Australia. (This volume)

Certini G (2005) Effects of fire on properties of forest soils: a review. *Oecologia* **143**, 1-10.

Clarke PJ, Knox, KJE, Wills KE, Campbell M (2005) Landscape patterns of woody plant response to crown fire: disturbance and productivity influence sprouting ability. *Journal of Ecology* **93**, 544–555.

Clarke MF (2008) Catering for the needs of fauna in fire management: science or just wishful thinking? *Wildlife Research* **35**, 385–394.

Cook GD, Jackson S and Williams RJ A revolution in northern Australian fire management: recognition of Indigenous knowledge, practice and management (This volume)

Driscoll DA, Lindenmayer DB, Bennett AF, Bode M, Bradstock RA, Cary GJ, Clarke MF, Dexter N, Fensham R, Friend G, Gill AM, James S, Kay G, Keith DA, MacGregor C, Possingham HP, Russell-Smith J, Salt DA, Watson JEM, Williams RJ and York A (2010) Fire management for biodiversity conservation: Key research questions and our capacity to answer them. *Biological Conservation* **143,** 1928–1939.

Edwards AC and Russell-Smith J (2009) Ecological thresholds and the status of fire-sensitive vegetation in western Arnhem Land, northern Australia: implications for management. *International Journal of Wildland Fire* **18**, 127 – 146.

Ellis S, Kanowski P and Whelan R (2004) 'National Inquiry on Bushfire Mitigation and Management'. Commonwealth of Australia, Canberra.

Enright NJ, Keith DA, Clarke MF and Miller BP Australian sclerophyllous shrubby ecosystems: heathlands, heathy woodlands and mallee woodlands (This volume)

Esplin B, Gill AM and Enright N (2003) 'Report of the Inquiry into the 2002-2003 Victorian Bushfires'. State Government of Victoria, Melbourne. 370p.

Faivre N, Roche P, Boer MM, McCaw L and Grierson PF (2011) Characterization of landscape pyrodiversity in Mediterranean environments: contrasts and similarities between south-western Australia and south-eastern France. *Landscape Ecology* **26**, 557–571.

Fensham RJ Fire regimes in Australia's tropical savanna landscapes: perspectives, paradigms and paradoxes (This Volume)

Gill AM (1975) Fire and the Australian flora: a review. *Australian Forestry* **38**, 4–25.

Gill AM, Groves RH, Noble IR (Eds) (1981) *Fire and the Australian Biota*. Australian Academy of Science, Canberra.

Gill AM (1981) Adaptive responses of Australian vascular plants to fires. In *Fire and the Australian Biota*. (Eds AM Gill, RH Groves and IR Noble) pp. 243–271. AUSTRALIAN ACADEMY OF SCIENCE, Canberra.

Gill AM Bushfires and biodiversity in southern Australian forests (This volume)

Gill and Cary in review

Gill AM (2008) *Underpinnings of Fire Management for the Conservation of Biodiversity in Reserves*. Victorian Department of Sustainability and Environment, Melbourne.[http://www.dse.vic.gov.au/DSE/nrenfoe.nsf/LinkView/D605713F058416B3CA257546008199898234596C0DA9C1ADCA256EF60010E43F]

Gill AM (2009) Fire, science and society at the rural-urban interface. *Proceedings of the Royal Society of Queensland* **115**, 153-160.

Gill AM and Stephens SL (2009) Scientific and social challenges for the management of fire-prone wildland-urban interfaces. *Environmental Research Letters* **4**, 1-10.

Gill AM, Ryan PG, Moore PHR, Gibson M (2000) Fire regimes of World Heritage Kakadu National Park, Australia *Austral Ecology* **25**, 616–625.

Gill AM, Bradstock RA and Williams JE (2002) Fire regimes and biodiversity: legacy and vision. *Flammable Australia: The Fire Regimes and Biodiversity of a Continent* (Eds RA Bradstock, JE Williams and AM Gill) pp. 429-446. CAMBRIDGE UNIVERSITY PRESS, Cambridge.

Gill AM and Allan G (2008) Large fires, fire effects and the fire-regime concept *International Journal of Wildland Fire* **17**, 688–695.

Gill AM, Allan G and Yates C (2003) Fire-created patchiness in Australian savannas. *International Journal of Wildland Fire* **12**, 323-331.

Haslem A, Kelly LT, Nimmo DG, Watson, SJ, Kenny SA, Taylor RS, Avitabile SC, Callister KE, Spence-Bailey LM, Bennett AF, and Clarke MF (2011) Habitat or fuel? Implications of long-term, post-fire dynamics for the development of key resources for fauna and fire. *Journal of Applied Ecology* doi: 10.1111/j.1365-2664.2010.01906.x

Hasson AEA, Mills GA, Timbal B and Walsh K (2009) Assessing the impact of climate change on extreme fire weather events over southeastern Australia. *Climate Research* **39**, 159–172. doi: 10.3354/cr00817.

Kattge J, Díaz S, Lavorel S, Prentice IC, Leadley P, Bönisch G, Garnier E, Westoby M, Reich PB, Wright IJ, Cornelissen JHC, Violle C, Harrison SP, van Bodegom PM, Reichstein M, Soudzilovskaia NA, Ackerly DD, Anand M, Atkin O, Bahn M, Baldocchi D, Blanco C, Blonder B, Bond W, Bradstock R, *et al.* (in press) TRY – a global database of plant traits. *Global Change Biology*

Kershaw AP, Clark JS, Gill AM and D'Costa DM (2002) A history of fire in Australia. In *Flammable Australia: The Fire Regimes and Biodiversity of a Continent.* (Eds RA Bradstock, AM Gill and JE Williams) pp. 3–25. CAMBRIDGE UNIVERSITY PRESS, Cambridge.

Keeley JE (2009) Fire intensity, fire severity and burn severity: a brief review and suggested usage. *International Journal of Wildland Fire* **18**, 116–126

Keeley JE, Bond WJ, Bradstock RA, Pausas JG, & Rundel PW (in press a) Fire Ecology, Evolution and Management in Mediterranean Climate Ecosystems CAMBRIDGE UNIVERSITY PRESS, Cambridge.

Keeley JE, Pausas JG, Rundel PW, Bond WJ, Bradstock RA (in press b) Fire as an evolutionary pressure shaping plant traits. *Trends in Plant Science*

Keith DA Functional traits: their roles in understanding and predicting biotic responses to fire regimes from individuals to landscapes (This volume)

King K, Cary G, Bradstock R, Chapman J, Pyrke A and Marsden-Smedley J (2006) Simulation of prescribed burning strategies in south west Tasmania, Australia: effects on unplanned fires, fire regimes and ecological management values. *International Journal of Wildland Fire* **15**, 527-540.

Krawchuk MA, Moritz MA, Parisien M-A, Van Dorn J and Hayhoe K (2009*a*) Global pyrogeography: the current and future distribution of wildfire. *PLoS ONE* **4**, e5102.

Lane PNJ, Feikema PM, Sherwin CB, Peel MC, Freebairn AC (2010) Modelling the long term water yield impact of wildfire and other forest disturbance in Eucalypt forests. *Environmental Modelling & Software* **25**, 467- 478

Lehmann CER, Archibald SA, Hoffmann WA, Bond WJ (2011) Deciphering the distribution of the savanna biome. *New Phytologist*
doi: 10.1111/j.1469-8137.2011.03689.x

Lunt ID, Prober SM and Morgan JW How do fire regimes affect ecosystem structure, function and diversity in grasslands and grassy woodlands of southern Australia? (This volume)

Maier SW, Russell-Smith J Measuring and monitoring of contemporary fire regimes in Australia using satellite remote sensing (This volume)

Marlon JR, Bartlein PJ, Carcaillet C, Gavin, DG, Harrison SP, Higuera PE, Joos F, Power MJ and Prentice IC (2008) Climate and human influences on global biomass burning over the past two millennia. *Nature Geoscience* doi:10.1038/ngeo313

McAneney J, Chen K, Pitman A (2009) 100-years of Australian bushfire property losses: Is the risk significant and is it increasing? *Journal of Environmental Management* **90**, 2819-2822.

McCarthy MA, Gill AM and Bradstock RA (2001) Theoretical fire-interval distributions. *International Journal of Wildland Fire* **10,** 73-77.

Mell W, Jenkins MA, Gould J, Cheney P (2007) A physics-based approach to modelling grassland fires. *International Journal of Wildland Fire* **16**, 1–22.

Mooney SD, Harrison SP, Bartlein PJ, Daniau A–L, Stevenson J, Brownlie K, Buckman S, Cupper M, Luly J, Black M, Colhoun E, D'Costa D, Dodson J, Haberle S, Hope GS, Kershaw P, Kenyon C, McKenzie M and Williams N (2011) Late Quaternary fire regimes in Australia. *Quaternary Science Reviews* **30**, 28–46.

Mooney SD, Harrison SP, Bartlein PJ and Stevenson J The Prehistory of Fire in Australasia (This volume)

Moritz MA, Keeley JE, Johnson EA and Schaffner AA (2004) Testing a basic assumption of shrubland fire management: Does the hazard of burning increase with the age of fuels? *Frontiers in Ecology and the Environment* **2**, 67-72.

Murphy BP, Paron P, Prior LD, Boggs GS, Franklin DC , Bowman DMJS(2011) Using generalized autoregressive error models to understand fire–vegetation–soil feedbacks in a mulga–spinifex landscape mosaic. *Journal of Biogeograph*y **37**, 2169–2182.

Nano C, Clarke P and Pavey C Fire regimes in arid hummock grasslands and *Acacia* shrublands (This volume)

Mucina L, Wardell-Johnson GW (2011) Landscape age and soil fertility, climatic stability, and fire regime predictability: beyond the OCBIL framework. *Plant and Soil* DOI 10.1007/s11104-011-0734-x

Mutch RW, Rogers MJ, Stephens SL, and Gill AM (2011) Protecting lives and property in the wildland-urban interface: communities in Montana and southern California adopt Australian paradigm. *Fire Technology* **47**, 357-377.

Noble IR and Slatyer RO (1980) The use of vital attributes to predict successional changes in plant communities subject to recurrent disturbances. *Vegetatio* **43**, 5–21.

Parr CL and Andersen AN (2006) Patch mosaic burning for biodiversity conservation: a critique of the pyrodiversity paradigm. *Conservation Biology* **20**, 1610–1619.

Pausas JG, Bradstock RA, Keith DA, Keeley JE and the GCTE (Global Change and Terrestrial Ecosystems) Fire Network (2004) Plant functional traits in relation to fire in crown-fire ecosystems. *Ecology* **85**, 1085–1100.

Pausas J, Bradstock RA (2007) Plant persistence fire traits along a productivity and disturbance gradient in Mediterranean shrublands of SE Australia. *Global Ecology and Biogeography* ***16,*** 330-340.

Penman TD, Price O, Bradstock RA (in press) Bayes Nets as a method for analysing return for investment in fire management planning. *International Journal of Wildland Fire*

Price OF and Bradstock RA (2011) Quantifying the influence of fuel age and weather on the annual extent of unplanned fires in the Sydney region of Australia. *International Journal of Wildland Fire* **20**, 142–151.

Russell-Smith J, Yates CP, Whitehead PJ, Smith R, Craig R, Allan GE, Thackway R, Frakes R, Cridland S, Meyer MCP and Gill AM (2007) Bushfires 'down under': patterns and implications of contemporary Australian landscape burning. *International Journal of Wildland Fire* **16**, 361–377.

Shakesby RA, Wallbrink PJ, Doerr SH, English PM, Chafer CJ, Humphreys GS, Blake WH and Tomkins KM (2007) Distinctiveness of wildfire effects on soil erosion in south-east Australian eucalypt forests assessed in a global context. *Forest Ecology and Management* **238***,* 347-364.

Sullivan AL (2009) Wildland surface fire spread modelling, 1990–2007. 2: Empirical and quasi-empirical models. *International Journal of Wildland Fire* **18**, 369–386.

Sullivan A and McCaw L (2009) 'Fire behaviour investigation'. Victorian 2009 Bushfire Research Response, Final Report October 2009. Bushfire CRC, Melbourne. ISBN: 978-0-9806759-8-6

Sullivan AL, McCaw WL, Cruz MG, Matthews S and Ellis PF Fuel, Fire Weather and Fire Behaviour in Australian Ecosystems (This volume)

Teague B, McLeod R and Pascoe S (2010) 'Final report 2009 Victorian Bushfires Royal Commission'. Parliament of Victoria, Australia. ISBN 978-0-9807408-1-3

van Wilgen B (2009) The evolution of fire management practices in savanna protected areas in South Africa. *South African Journal of Science* **105**, 343-349.

van Wilgen BW, Forsyth GG , de Klerk H, Das S, Khuluse S and Schmitz P (2010) Fire management in Mediterranean-climate shrublands: a case study from the Cape fynbos, South Africa. Journal of Applied Ecology **47**, 631-638.

Vertessy R, Watson, FGR, O'Sullivan, SK (2001) Factors determining relations between stand age and catchment water balance in mountain ash forests. *Forest Ecology and Management* **143**, 13-26.

Vivian LM, Doherty MD and Cary GJ (2010) Classifying the fire-response traits of plants: how reliable are species-level classifications? *Austral Ecology* **35**, 264-273.

White I, Wade A, Worthy M (2006) The vulnerability of water supply catchments to bushfires: impacts of the January 2003 wildfires on the Australian Capital Territory. *Australian Journal of Water Resources* **10**, 179-193.

Williams RJ, Bradstock RA (2008). Large fires and their ecological consequences: introduction to the special issue. *International Journal of Wildland Fire* **17**, 685–687.

Williams RJ, Bradstock RA, Cary GJ, Enright NJ, Gill AM, Liedloff AC, Lucas C, Whelan RJ, Andersen AN, Bowman DMJS, Clarke PJ, Cook GD, Hennessy KJ and York A (2009) 'Interactions between climate change, fire regimes & biodiversity in Australia – a preliminary assessment'. Report to the Department of Climate Change and Department of Environment, Water, Heritage and the Arts, Canberra. ISBN:978-1-921298-62-2.

Williams RJ, Bradstock RA, Barrett D, Beringer J, Boer MM, Cary GJ, Cook GD, Gill AM, Hutley LBW, Keith H, Maier S, Meyer CP, Price O, Roxburgh S and Jeremy Russell-Smith J Fire regimes and carbon in Australian vegetation (This volume)

York A, Bell TL and Weston CJ Fire regimes and soil-based ecological processes: implications for biodiversity (This volume)